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ABSTRACT

The main objective of this project is to measure heat of dissolution of CO₂ in carefully selected mixed alkanolamine solvent systems, and provide such directly measured data that might be used for efficient design of CO₂ capture processes, or for better understanding of thermodynamics of CO₂- alkanolamine systems. Carbon dioxide is one of the major greenhouse gases, and the need for stabilization of its composition in earth's atmosphere is vital for the future of mankind. Although technologies are available for capture and storage of CO₂, these technologies are far too expensive for economical commercialization. Reduction of cost would require research for refinement of the technology. For more economical CO₂ capture and regeneration, there is a need for development of more efficient solvent systems. In this project we will extend the thermodynamic database by measuring heat of solution data of CO₂ in mixed solvents made of MEA (monoethanolamine), MDEA (methyldiethanolamine), piperazine, and water. Mixed solvents of different compositions will be selected and in each case data will be measured at temperatures 40 and 80C and various partial pressures of CO₂. At the end of the project, observations, conclusions, and recommendations will be derived for the choice of mixed solvents for efficient CO₂ capture with potential for commercialization.

EXECUTIVE SUMMARY

The main objective of this project is to measure heat of dissolution of CO₂ in carefully selected mixed alkanolamine solvent systems, and provide such directly measured data that might be used for efficient design of CO₂ capture processes, or for better understanding of thermodynamics of CO₂- alkanolamine systems. Carbon dioxide is one of the major greenhouse gases, and the need for stabilization of its composition in earth's atmosphere is vital for the future of mankind. Although technologies are available for capture and storage of CO₂, these technologies are far too expensive for economical commercialization. Reduction of cost would require research for refinement of the technology. For more economical CO₂ capture and regeneration, there is a need for development of more efficient solvent systems. In this project we will extend the thermodynamic database by measuring heat of solution data of CO₂ in mixed solvents made of MEA (monoethanolamine), MDEA (methyldiethanolamine), piperazine, and water. Mixed solvents of different compositions will be selected and in each case data will be measured at temperatures 15, 40 and 80C and various partial pressures of CO₂. At the end of the project, observations, conclusions, and recommendations will be derived for the choice of mixed solvents for efficient CO₂ capture with potential for commercialization.

Data measurements for CO₂ in aqueous MEA, MDEA and mixtures of MEA and MDEA were completed and reported previously. During the current period of performance, April 2006 to September 2006, data measurements for CO₂ in aqueous mixtures of MDEA and piperazine were completed. The results of these measurements are reported. Some preliminary measurements have been made using potassium fluoride as an additive to aqueous MDEA solutions. Results do not show any obvious improvements. Some more measurements will be carried out before the next reporting period.

Efforts have begun to analyze and write up all the data measured into journal publications. A paper is currently in preparation that will include our solubility and enthalpy data for CO₂ in aqueous MEA and MDEA solutions, a compilation of all literature data for these systems, and correlations for CO₂ solubility as a function of temperature pressure and amine concentration. The objective is to provide data correlations that will be very useful in optimizing design of CO₂ removal processes.

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1. Introduction

Carbon dioxide is one of the major greenhouse gases, and the need for stabilization of its composition in earth's atmosphere is vital for the future of mankind. Although technologies are available for capture and storage of CO₂, these technologies are far too expensive for economical commercialization. Reduction of cost would require research for refinement of the technology. The idea of capturing CO₂ from the flue gas of power plants did not start with concern about the greenhouse effect. Rather, it gained attention as a possible economic source of CO₂, especially for use in enhanced oil recovery operations where CO₂ is injected into oil reservoirs to increase the mobility of the oil and, therefore, the productivity of the reservoir. Several commercial CO₂ capture plants were constructed in the late 1970s and early 1980s in the US. The North American Chemical Plant in Trona, CA, which uses the carbonation of brine to produce CO₂, started operation in 1978 and is still operating today. However, when the price of oil dropped in mid-1980s, the recovered CO₂ was too expensive for enhanced oil recovery operations and all of the other CO₂ capture plants were closed.

Historically, CO₂ capture processes have required significant amounts of energy, which reduces the power plant's net power output. For example, the output of a 500 MW (net) coal-fired power plant may be reduced to 400 MW (net) after CO₂ capture. This imposes an "energy penalty" of 20%. The energy penalties of current capture technologies range from about 30% for conventional coal to about 15% for advanced coal. It is desired that in the next decade these numbers be brought to 50% of their current values.

To date, all commercial CO₂ capture plants use processes based on chemical absorption with the monoethanolamine (MEA) solvent. MEA was developed over 60 years ago as a general, non-selective solvent to remove acid gases, such as CO₂ and H₂S, from natural gas streams. The process was modified to incorporate inhibitors to resist solvent degradation and equipment corrosion when applied to CO₂ capture from flue gas. Also, the solvent strength was kept relatively low, resulting in large equipment sizes and high regeneration energy requirements. The process allowed flue gas to contact an MEA solution in the absorber. The MEA selectively absorbed the CO₂ and was then sent to a stripper. In the stripper, the CO₂-rich MEA solution was heated to release almost pure CO₂. The lean MEA solution was then recycled to the absorber.

Other processes have been considered to capture CO₂ from the flue gas of a power plant, e.g., membrane separation, cryogenic fractionation, and adsorption using molecular sieves. These processes are even less efficient and more expensive than the chemical absorption. The reason can be attributed to the very low CO₂ partial pressure in the flue gas. Therefore, a high priority research need is to formulate new solvents that can significantly reduce the energy penalty associated with chemical absorption. The new solvents must increase the loading (amount of CO₂ dissolved per unit amount of solvent), and the rate of CO₂ dissolution while maintaining a low heat of solution, so as to minimize the energy requirements during the solvent regeneration.

For the processes based on the absorption of CO₂ by aqueous alkanolamines, the energy penalty or the cost of the process depends mostly on three factors: (1) the loading of CO₂ (moles of CO₂ absorbed per mole of amine), (2) the rate of CO₂ absorption, and (3) the energy requirement for the release of CO₂ in the stripper. For a number of solvents, detailed studies are available in the literature for the first two factors. Aqueous MEA solvents suffer from the limitation that CO₂ loading cannot exceed much higher than 0.5. An amine that is considered as a potential replacement for MEA is methyldiethanolamine (MDEA) because of the high loading of CO₂ (approaching 1) which is attributed to the stoichiometry of the reaction forming carbamate. However, the rate of CO₂ absorption by MDEA is too low for commercial applications. Mixed solvents containing MEA and MDEA, and diethanolamine (DEA) and MDEA in water seem to provide good solutions to give high absorption rates as well as CO₂ loading. Recently researchers have also started looking at other additives to aqueous MEA and MDEA mixtures to enhance solubility and rate of absorption of CO₂. These include sulfolane, N-methylpyrrolidone (NMP), and piperazine (PZ). Of these, piperazine seems to be the most effective in increasing the solubility of CO₂. The data available in the literature indicate that aqueous mixtures of MEA, MDEA and piperazine have potential to provide a solvent system superior to aqueous MEA solvent of the current commercial capture plants. However, a true determination of this is difficult without a detailed study of the relative energy requirements for each of the solvents. Such a study is not available in the literature, mostly because of lack of experimental data on the heats of dissolution of CO₂ in the aqueous alkanolamine solvents. Data are available only for a few systems and at limited conditions.

For more economical CO₂ capture and regeneration, there is a need for development of more efficient solvent systems. In this project we will extend the thermodynamic database by measuring heat of solution data of CO₂ in mixed solvents made of MEA (monoethanolamine), MDEA (methyldiethanolamine), piperazine, and water. Mixed solvents of different compositions will be selected and in each case data will be measured at a few temperatures and at different concentrations of the aqueous solutions. At the end of the project, observations, conclusions, and recommendations will be derived for the choice of mixed solvents for efficient CO₂ capture with potential for commercialization.

2. Progress of Experimental Measurements

In this report we present the solubility and enthalpy data measured for CO₂ in aqueous MDEA-piperazine(PZ) mixtures. Data were measured at three temperatures, 15 C, 40 C, and 75 C, and for three mixture compositions with MDEA and PZ weight percents of 30-5, 32.5-6, and 30-10. The procedure for data measurements was the same as described in previous reports. The results for solubility (expressed as loading factor α which is defined as moles of CO₂ dissolved per mole of amine) and enthalpy are summarized in Table 1. Our results were compared with some experimental data available in the literature. The measured solubilities for (32.5+6) mixture at 40 and 75 C were compared with the data of Liu, Zhang and Xu, Ind. Eng. Chem Res. 1999, 38, 4032.

Our α values of 1.07 and 0.90 are somewhat higher than the literature values of 0.94 and 0.72. Also our measured heat of solution, for (30+10) mixture at 40 C, of -53 kJ/mol CO₂ is somewhat lower than the literature value of -81.2 kJ/mol CO₂ (Schafer, Mather and Marsh, Fluid Phase Equil., 2002, 194-197, 929). However, the literature data in this area are known to have a large scatter, and our data show consistent trends with the data for pure MDEA solutions. Detailed data for each run that give the heats of solution from low concentrations of CO₂ to the saturation point are shown in Tables 2-10 and Figures 2-10. Figure 1 shows the comparison of results for 30 wt% MDEA solution, 30-10 wt% mixture of MDEA and PZ, and 30-8 wt% mixture of MDEA and potassium fluoride. A brief analysis of the data shows that there is no advantage of adding PZ to MDEA solutions over using MEA+ MDEA mixtures. No further data measurements with PZ are therefore recommended. Some additional runs with inorganic salt additives will continue and results will be analyzed to see if any enhancements are observed.

3. Data Analysis and Other Current Work

An observation our heat of solution data indicate that the heat of solution per mole of CO₂ is fairly constant with CO₂ loading at low CO₂ concentrations, but it decreases closer to the saturation concentration. Attempts are being made to model this behavior, and obtain expressions for heats of mixing as function of CO₂ concentration. The results will be presented when completed.

Efforts have begun to analyze and write up all the data measured into journal publications. A paper is currently in preparation that will include our solubility and enthalpy data for CO₂ in aqueous MEA and MDEA solutions, a compilation of all literature data for these systems, and correlations for CO₂ solubility as a function of temperature pressure and amine concentration. The objective is to provide data correlations that will be very useful in optimizing design of CO₂ removal processes.

4. Conclusions and Plans for the Next Quarter

In the next quarter, measurements with aqueous mixed solvents containing inorganic salts will be completed, and based on the results recommendations for future investigations in this area will be made. The data analysis for all measured data will be completed, and results will be presented in 1 or 2 journal publications.

Table 1: Solubility and Enthalpy data for CO₂ in aqueous MDEA+PZ mixed solvent

<i>MDEA+PZ solution</i>				
<i>Temp °C</i>	<i>MDEA+PZ Wt %</i>	<i>Solubility, α mol CO₂/mol amine</i>	<i>kJ / mol CO₂</i>	<i>kJ / mol Amine</i>
15	30+0	1.26	-39	-49
	30+5	1.12	-33	-40.3
	32.5+6	1.15	-45	-52
	30+10	1.19	-45.5	-54
40	30+0	1.17	-43.2	-50.2
	30+5	1.14	-49	-56.5
	32.5+6	1.07	-53.9	-57.7
	30+10	1.10	-53	-58
75	30+0	0.82	-52.8	-43.2
	30+5	0.93	-57.6	-53.5
	32.5+6	0.90	-59	-52
	30+10	0.92	-61.5	-55.9

Table 2: Data for (30-5) wt% mixture of MDEA+PZ at 15 C

CO ₂ (sccm)	CO ₂ mol/S	Amine (ml/min)	Amine (mol/S)	loading	Avg H	H (KJ/mol CO ₂)	H (KJ/mol Amine)
0.2	1.468E-07	0.03	1.5785E-06	0.093	-6	-40.877	-3.801
0.2	1.468E-07	0.018	9.47102E-07	0.155	-6	-40.877	-6.335
0.22	1.615E-07	0.016	8.41868E-07	0.192	-6.6	-40.877	-7.840
0.24	1.761E-07	0.013	6.84018E-07	0.258	-7.1	-40.310	-10.380
0.28	2.055E-07	0.01	5.26168E-07	0.391	-8.2	-39.904	-15.584
0.34	2.495E-07	0.009	4.73551E-07	0.527	-9.95	-39.876	-21.011
0.42	3.082E-07	0.009	4.73551E-07	0.651	-12.3	-39.904	-25.974
0.46	3.376E-07	0.008	4.20934E-07	0.802	-13.3	-39.396	-31.596
0.36	2.642E-07	0.005	2.63084E-07	1.004	-10	-37.849	-38.011
0.38	2.789E-07	0.005	2.63084E-07	1.060	-10.4	-37.292	-39.531
0.4	2.936E-07	0.005	2.63084E-07	1.116	-10.5	-35.768	-39.911
0.38	2.789E-07	0.004	2.10467E-07	1.325	-8.5	-30.479	-40.386
0.24	1.761E-07	0.002	1.05234E-07	1.674	-4.2	-23.845	-39.911

Table 3: Data for (32.5-6) wt% mixture of MDEA+PZ at 15 C

CO2 (sccm)	CO2 mol/S	Amine (ml/min)	Amine (mol/S)	loading	Avg H	H (KJ/mol CO2)	H (KJ/mol Amine)
0.2	1.468E-07	0.02	1.16472E-06	0.126	-7.6	-51.778	-6.525
0.2	1.468E-07	0.026	1.51413E-06	0.097	-7.6	-51.778	-5.019
0.34	2.495E-07	0.026	1.51413E-06	0.165	-12.9	-51.698	-8.520
0.42	3.082E-07	0.026	1.51413E-06	0.204	-15.9	-51.583	-10.501
0.72	5.284E-07	0.026	1.51413E-06	0.349	-27	-51.097	-17.832
1	7.339E-07	0.026	1.51413E-06	0.485	-37.5	-51.097	-24.767
1.24	9.1E-07	0.026	1.51413E-06	0.601	-46	-50.547	-30.380
1.54	1.13E-06	0.026	1.51413E-06	0.746	-56	-49.548	-36.985
1.82	1.336E-06	0.026	1.51413E-06	0.882	-65	-48.664	-42.929
2	1.468E-06	0.026	1.51413E-06	0.969	-70.8	-48.235	-46.760
2.2	1.615E-06	0.026	1.51413E-06	1.066	-77	-47.690	-50.854
2.4	1.761E-06	0.026	1.51413E-06	1.163	-78.7	-44.681	-51.977
2.5	1.835E-06	0.026	1.51413E-06	1.212	-78.7	-42.894	-51.977
2.86	2.099E-06	0.026	1.51413E-06	1.386	-78.8	-37.542	-52.043

Table 4: Data for (30-10) wt% mixture of MDEA+PZ at 15 C

CO2 (sccm)	CO2 mol/S	Amine (ml/min)	MDEA (mol/S)	loading	Avg H	H (KJ/mol CO2)	H (KJ/mol Amine)
0.28	2.055E-07	0.025	1.56868E-06	0.131	-11.5	-55.963	-7.331
0.38	2.789E-07	0.026	1.63143E-06	0.171	-15.6	-55.938	-9.562
0.46	3.376E-07	0.024	1.50594E-06	0.224	-18.9	-55.984	-12.550
0.6	4.403E-07	0.024	1.50594E-06	0.292	-24.6	-55.866	-16.335
0.6	4.403E-07	0.02	1.25495E-06	0.351	-24.6	-55.866	-19.602
1	7.339E-07	0.026	1.63143E-06	0.450	-41.1	-56.002	-25.193
1.4	1.027E-06	0.026	1.63143E-06	0.630	-57	-55.477	-34.939
1.8	1.321E-06	0.026	1.63143E-06	0.810	-72	-54.503	-44.133
2.1	1.541E-06	0.026	1.63143E-06	0.945	-79.5	-51.583	-48.730
2	1.468E-06	0.022	1.38044E-06	1.063	-72	-49.053	-52.157
2.2	1.615E-06	0.022	1.38044E-06	1.170	-74.5	-46.142	-53.968
1.9	1.394E-06	0.018	1.12945E-06	1.235	-61	-43.746	-54.008
2.1	1.541E-06	0.018	1.12945E-06	1.365	-61	-39.580	-54.008

Table 5: Data for (30-5) wt% mixture of MDEA+PZ at 40 C

CO2 (sccm)	CO2 mol/S	Amine (ml/min)	Amine (mol/S)	loading	Avg H	H (KJ/mol CO2)	H (KJ/mol Amine)
0.2	1.468E-07	0.02	1.05234E-06	0.139	-8.8	-59.954	-8.362
0.24	1.761E-07	0.015	7.89251E-07	0.223	-10.6	-59.897	-13.367
0.28	2.055E-07	0.015	7.89251E-07	0.260	-12.3	-59.856	-15.584
0.3	2.202E-07	0.015	7.89251E-07	0.279	-13.2	-59.954	-16.725
0.5	3.67E-07	0.02	1.05234E-06	0.349	-22	-59.954	-20.906
0.4	2.936E-07	0.015	7.89251E-07	0.372	-17.5	-59.613	-22.173
0.5	3.67E-07	0.015	7.89251E-07	0.465	-21.6	-58.864	-27.368
0.4	2.936E-07	0.01	5.26168E-07	0.558	-16.9	-57.569	-32.119
0.5	3.67E-07	0.01	5.26168E-07	0.697	-20.5	-55.866	-38.961
0.6	4.403E-07	0.01	5.26168E-07	0.837	-24	-54.503	-45.613
0.7	5.137E-07	0.01	5.26168E-07	0.976	-27	-52.557	-51.314
0.8	5.871E-07	0.01	5.26168E-07	1.116	-29.5	-50.245	-56.066
0.8	5.871E-07	0.009	4.73551E-07	1.240	-26.9	-45.817	-56.805
0.7	5.137E-07	0.007	3.68317E-07	1.395	-21	-40.877	-57.016
0.7	5.137E-07	0.006	3.15701E-07	1.627	-18	-35.038	-57.016

Table 6: Data for (32.5-6) wt% mixture of MDEA+PZ at 40 C

CO2 (sccm)	CO2 mol/S	Amine (ml/min)	Amine (mol/S)	loading	Avg H	H (KJ/mol CO2)	H (KJ/mol Amine)
1	7.339E-07	0.12	6.98829E-06	0.105	-48.685	-66.337	-6.967
1	7.339E-07	0.05	2.91179E-06	0.252	-48.818	-66.519	-16.766
1.1	8.073E-07	0.05	2.91179E-06	0.277	-53.173	-65.866	-18.261
1.4	1.027E-06	0.05	2.91179E-06	0.353	-66.255	-64.484	-22.754
1.5	1.101E-06	0.05	2.91179E-06	0.378	-70.17	-63.742	-24.099
1.5	1.101E-06	0.04	2.32943E-06	0.473	-68.833	-62.527	-29.549
1.5	1.101E-06	0.03	1.74707E-06	0.630	-66.339	-60.262	-37.971
1.5	1.101E-06	0.02	1.16472E-06	0.945	-61.932	-56.258	-53.173
1.7	1.248E-06	0.02	1.16472E-06	1.071	-67.185	-53.850	-57.684
1.1	8.073E-07	0.01	5.82358E-07	1.386	-33.624	-41.650	-57.738

Table 7: Data for (30-10) wt% mixture of MDEA+PZ at 40 C

CO2 (sccm)	CO2 mol/S	Amine (ml/min)	Amine (mol/S)	loading	Avg H	H (KJ/mol CO2)	H (KJ/mol Amine)
0.2	1.468E-07	0.018	1.12945E-06	0.130	-9.8	-66.766	-8.677
0.22	1.615E-07	0.015	9.4121E-07	0.172	-10.8	-66.890	-11.475
0.24	1.761E-07	0.015	9.4121E-07	0.187	-11.75	-66.710	-12.484
0.2	1.468E-07	0.008	5.01979E-07	0.292	-9.65	-65.745	-19.224
0.2	1.468E-07	0.007	4.39231E-07	0.334	-9.5	-64.723	-21.629
0.2	1.468E-07	0.006	3.76484E-07	0.390	-9.4	-64.041	-24.968
0.2	1.468E-07	0.005	3.13737E-07	0.468	-9.3	-63.360	-29.643
0.24	1.761E-07	0.005	3.13737E-07	0.561	-10.9	-61.884	-34.743
0.3	2.202E-07	0.005	3.13737E-07	0.702	-13.3	-60.408	-42.392
0.36	2.642E-07	0.005	3.13737E-07	0.842	-15.4	-58.288	-49.086
0.42	3.082E-07	0.005	3.13737E-07	0.982	-17.2	-55.801	-54.823
0.46	3.376E-07	0.005	3.13737E-07	1.076	-18.1	-53.615	-57.692
0.5	3.67E-07	0.005	3.13737E-07	1.170	-18.2	-49.598	-58.010
0.52	3.816E-07	0.005	3.13737E-07	1.216	-18.2	-47.690	-58.010
0.6	4.403E-07	0.005	3.13737E-07	1.404	-18.2	-41.332	-58.010

Table 8: Data for (30-5) wt% mixture of MDEA+PZ at 75 C

CO2 (sccm)	CO2 mol/S	Amine (ml/min)	Amine (mol/S)	loading	Avg H	H (KJ/mol CO2)	H (KJ/mol Amine)
0.2	1.468E-07	0.06	3.15701E-06	0.046	-10.55	-71.876	-3.342
0.6	4.403E-07	0.06	3.15701E-06	0.139	-31.75	-72.103	-10.057
0.8	5.871E-07	0.06	3.15701E-06	0.186	-42	-71.536	-13.304
1	7.339E-07	0.06	3.15701E-06	0.232	-52	-70.854	-16.471
1.4	1.027E-06	0.06	3.15701E-06	0.325	-71.3	-69.394	-22.585
2	1.468E-06	0.055	2.89392E-06	0.507	-97.4	-66.358	-33.657
2.7	1.982E-06	0.055	2.89392E-06	0.685	-125	-63.082	-43.194
3	2.202E-06	0.05	2.63084E-06	0.837	-133	-60.408	-50.554
0.2	1.468E-07	0.003	1.5785E-07	0.930	-8.45	-57.569	-53.532
0.22	1.615E-07	0.003	1.5785E-07	1.023	-8.5	-52.645	-53.848
0.24	1.761E-07	0.003	1.5785E-07	1.116	-8.5	-48.258	-53.848
0.28	2.055E-07	0.003	1.5785E-07	1.302	-8.5	-41.364	-53.848

Table 9: Data for (32.5-6) wt% mixture of MDEA+PZ at 75 C

CO2 (sccm)	CO2 mol/S	Amine (ml/min)	Amine (mol/S)	loading	Avg H	H (KJ/mol CO2)	H (KJ/mol Amine)
0.2	1.468E-07	0.025	1.45589E-06	0.101	-11.5	-78.348	-7.899
0.3	2.202E-07	0.024	1.39766E-06	0.158	-17.3	-78.576	-12.378
0.4	2.936E-07	0.024	1.39766E-06	0.210	-23	-78.348	-16.456
0.5	3.67E-07	0.023	1.33942E-06	0.274	-28.3	-77.122	-21.128
0.7	5.137E-07	0.023	1.33942E-06	0.384	-38.5	-74.942	-28.744
0.9	6.605E-07	0.023	1.33942E-06	0.493	-47	-71.157	-35.090
1.2	8.807E-07	0.023	1.33942E-06	0.658	-58.6	-66.539	-43.750
1.4	1.027E-06	0.023	1.33942E-06	0.767	-64.7	-62.971	-48.304
1.6	1.174E-06	0.023	1.33942E-06	0.877	-69.5	-59.187	-51.888
1.7	1.248E-06	0.023	1.33942E-06	0.931	-69.9	-56.026	-52.187
1.9	1.394E-06	0.023	1.33942E-06	1.041	-69.9	-50.129	-52.187
2.2	1.615E-06	0.023	1.33942E-06	1.205	-69.9	-43.293	-52.187

Table 10: Data for (30-10) wt% mixture of MDEA+PZ at 75 C

CO2 (sccm)	CO2 mol/S	MDEA (ml/min)	MDEA (mol/S)	loading	Avg H	H (KJ/mol CO2)	H (KJ/mol MDEA)
0.36	2.64E-07	0.06	3.7648E-06	0.070	-20.25	-76.645	-5.379
0.76	5.58E-07	0.06	3.7648E-06	0.148	-42.8	-76.735	-11.368
0.9	6.61E-07	0.06	3.7648E-06	0.175	-50.5	-76.456	-13.414
1.3	9.54E-07	0.06	3.7648E-06	0.253	-71.5	-74.942	-18.992
1.8	1.32E-06	0.06	3.7648E-06	0.351	-97	-73.428	-25.765
2.3	1.69E-06	0.06	3.7648E-06	0.448	-121	-71.684	-32.139
2.8	2.05E-06	0.06	3.7648E-06	0.546	-142.2	-69.200	-37.771
3.4	2.5E-06	0.06	3.7648E-06	0.663	-167	-66.927	-44.358
0.4	2.94E-07	0.006	3.7648E-07	0.780	-19	-64.723	-50.467
0.46	3.38E-07	0.006	3.7648E-07	0.897	-20.9	-61.909	-55.514
0.48	3.52E-07	0.006	3.7648E-07	0.936	-21.05	-59.755	-55.912
0.5	3.67E-07	0.006	3.7648E-07	0.975	-21	-57.228	-55.779
0.64	4.7E-07	0.006	3.7648E-07	1.248	-21	-44.710	-55.779

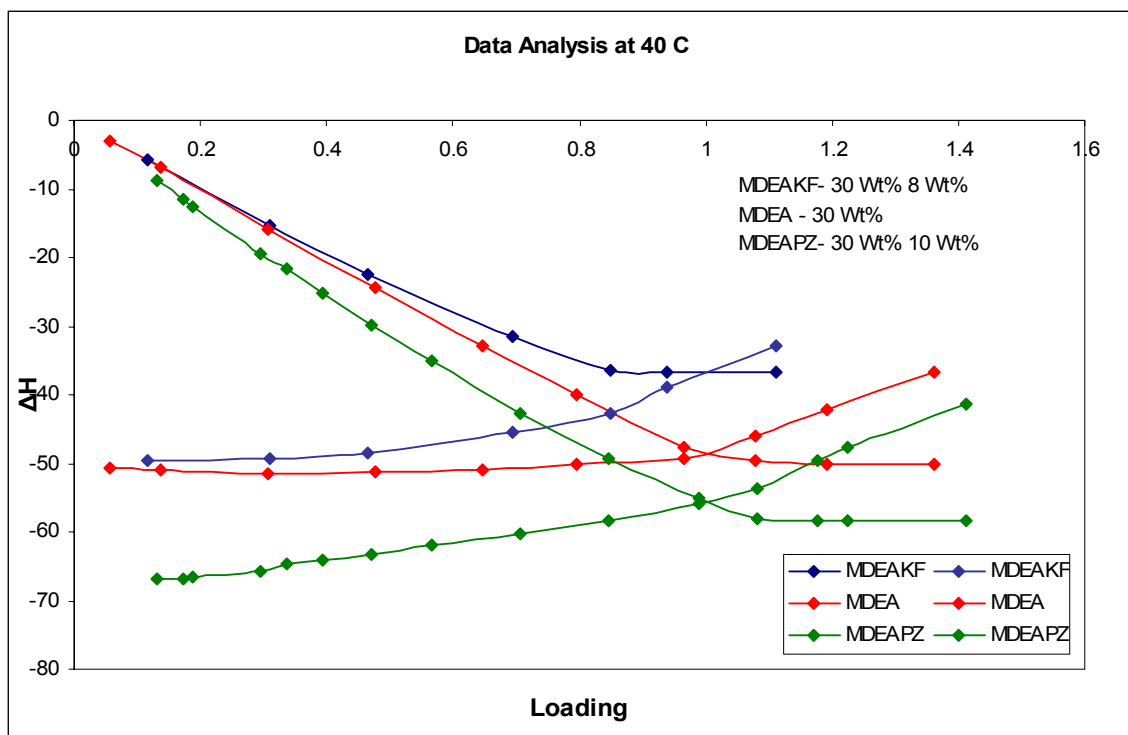


Figure 1: Heat of solution of CO₂ in aqueous MDEA, MDEA-PZ mixture and MDEA-KF mixture at 40 C.

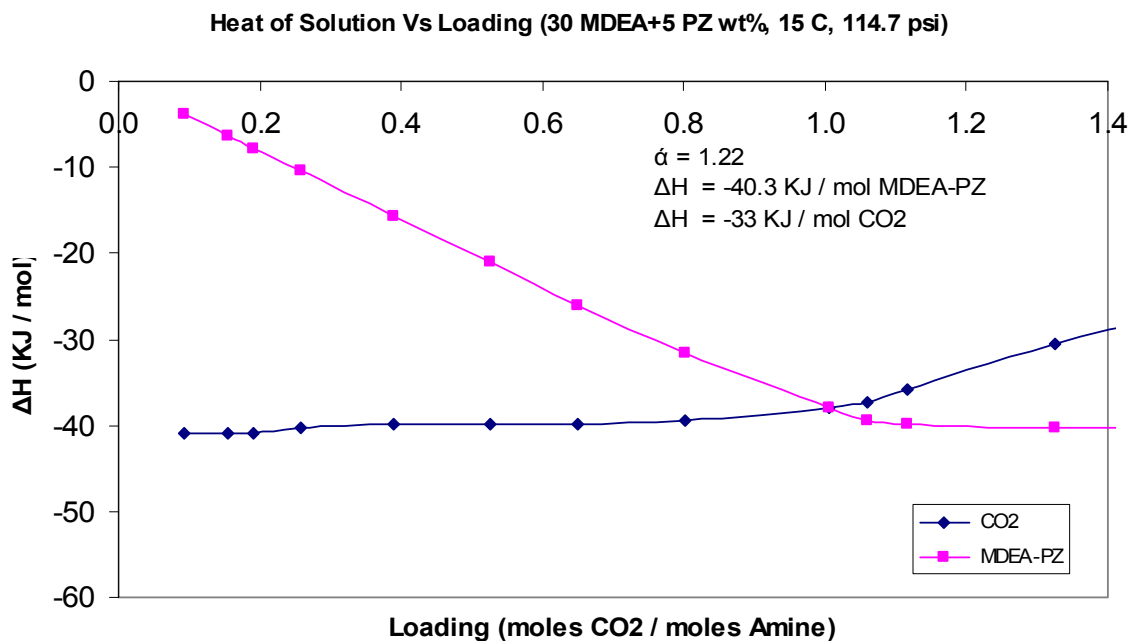


Figure 2: Heat of solution of CO₂ in aqueous MDEA-PZ (30%-5%) mixture at 15 C.

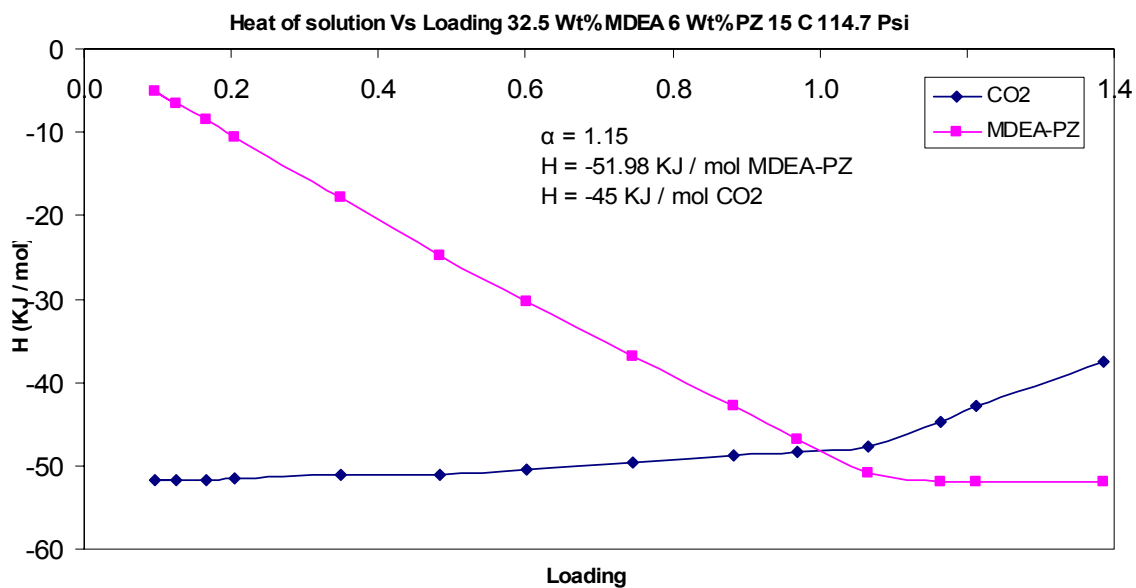


Figure 3: Heat of solution of CO₂ in aqueous MDEA-PZ (32.5%-6%) mixture at 15 C.

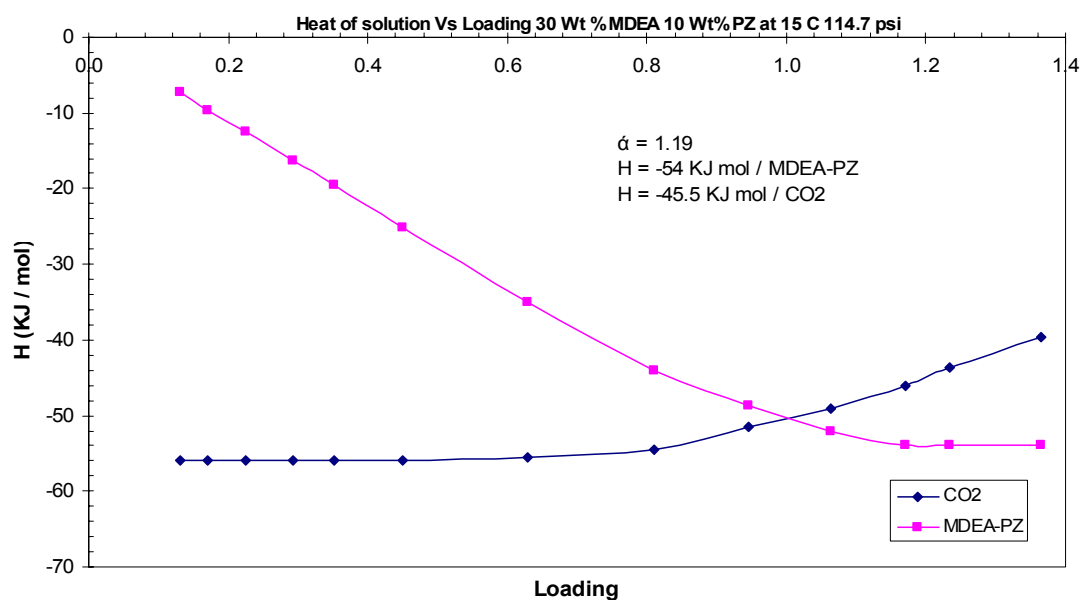


Figure 4: Heat of solution of CO₂ in aqueous MDEA-PZ (30%-10%) mixture at 15 C.

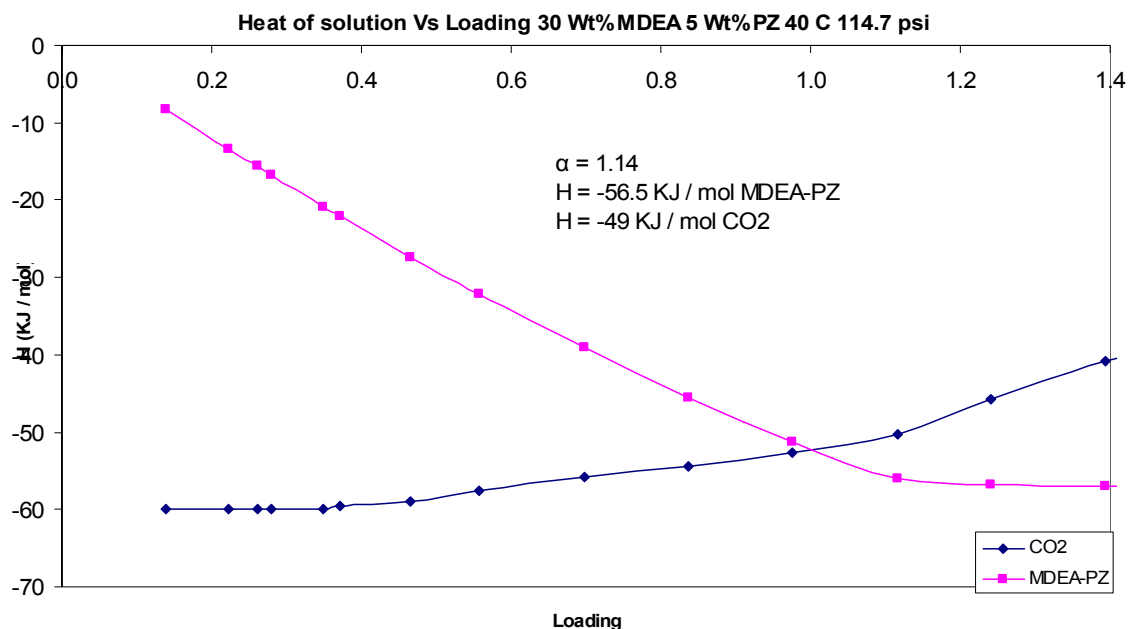


Figure 5: Heat of solution of CO₂ in aqueous MDEA-PZ (30%-5%) mixture at 40 C.

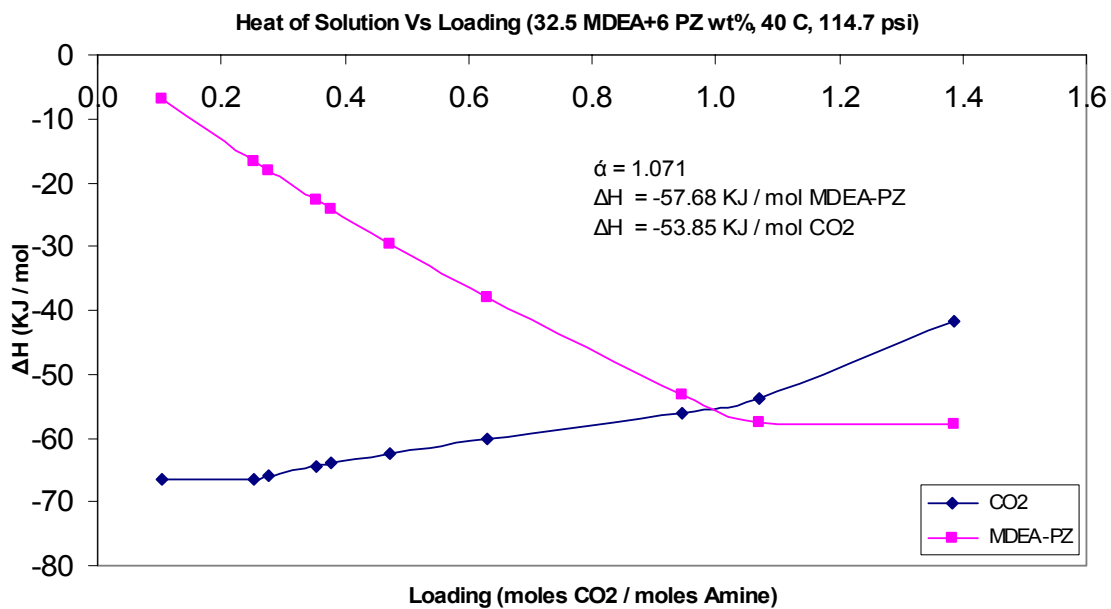


Figure 6: Heat of solution of CO₂ in aqueous MDEA-PZ (32.5%-6%) mixture at 40 C.

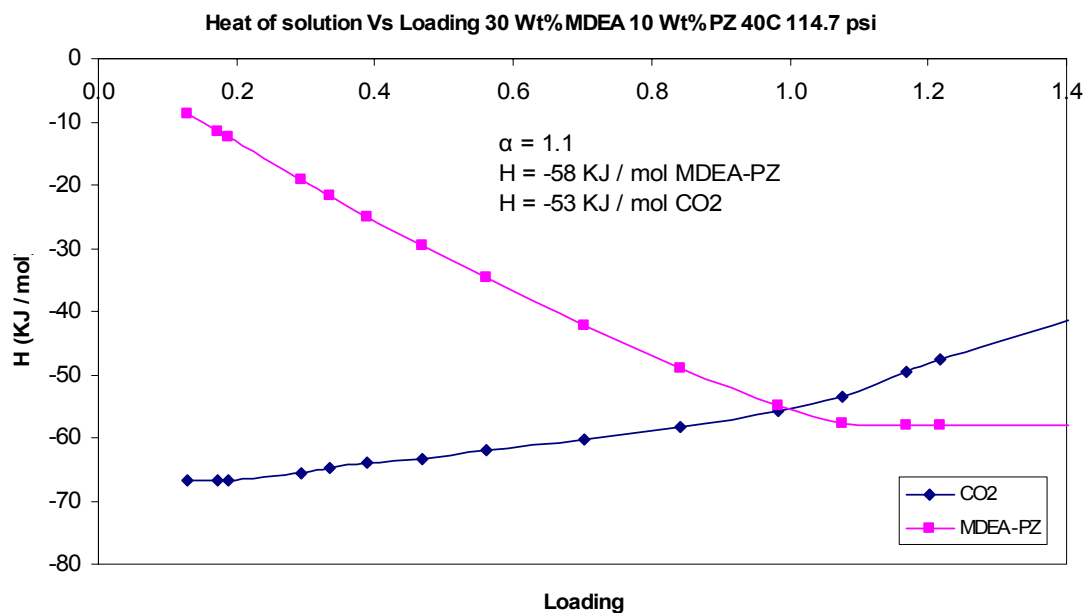


Figure 7: Heat of solution of CO₂ in aqueous MDEA-PZ (30%-10%) mixture at 40 C.

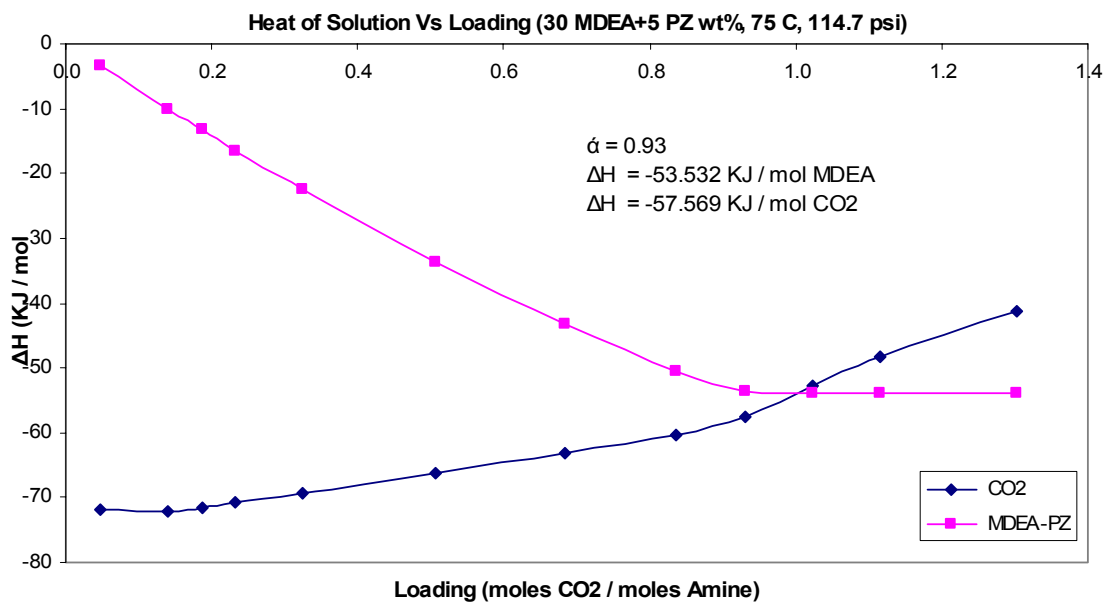


Figure 8: Heat of solution of CO₂ in aqueous MDEA-PZ (30%-5%) mixture at 75 C.

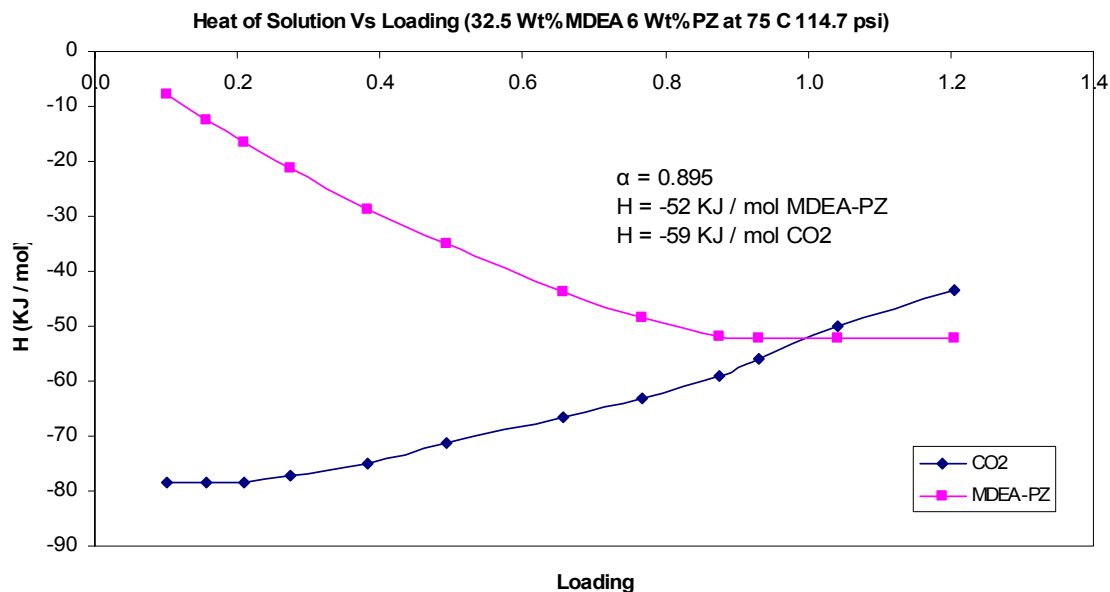


Figure 9: Heat of solution of CO_2 in aqueous MDEA-PZ (32.5%-6%) mixture at 75 C.

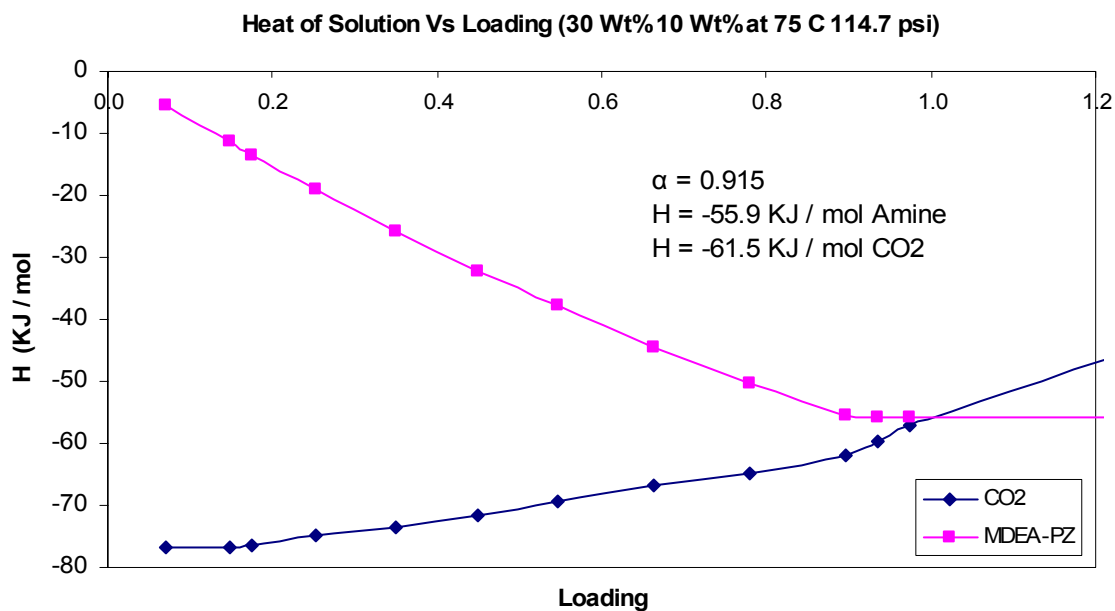


Figure 10: Heat of solution of CO_2 in aqueous MDEA-PZ (30%-10%) mixture at 75 C.